Cummins Westport Spark-Ignited (SI) and High Pressure Direct Injection (HPDI) Natural Gas Engines

NGVTF
Natural Gas Vehicle Technology Forum

January 2003

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Outline

- **Introduction**
  - Cummins-Westport Inc.
  - SI and HPDI plans
- **SI Technology**
  - Products and technology
  - Benefits
  - Outlook on technology developments
- **HPDI Technology**
  - Technology Description
  - Benefits
  - Outlook on technology developments

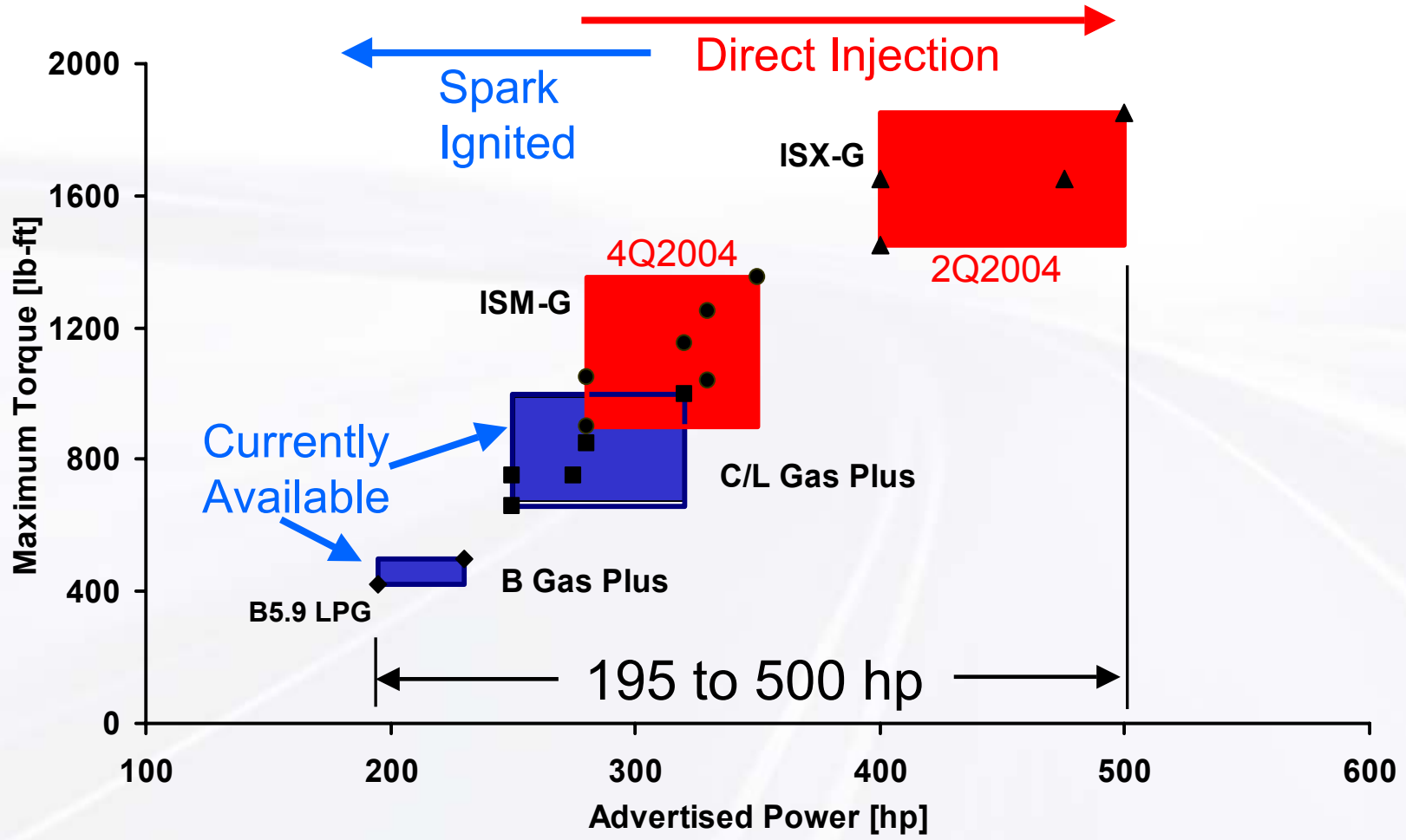
Cummins Westport Inc.

- **Engine company formed March 2001**
- **A 50/50 JV between Cummins, Inc. and Westport Innovations, Inc.**
- **Created to become a leader in the rapidly emerging world-wide market for alternative fuel engines**
  - High performance
  - Low emission
  - Economically viable
- **Bringing to market a comprehensive line of gaseous fuel engine products**
  - Using best available technologies
  - Engineered into Cummins line of automotive products
- **Products based on current and future technological developments by both Cummins and Westport**

How We See the Future

- Reciprocating engines, particularly HD diesels, will continue to dominate transportation and industrial markets for decades
- Drive will continue for engines with reduced environmental and social impacts (atmospheric pollutants, GHG, oil imports)
- Natural gas is a natural choice – it's the only mainstream fuel cheaper than diesel, is already widely available and can be easily be delivered to customers
- We need to be creative to provide better, more economical and complete solutions for fleets

CWI NG Engines – Current and Planned Offerings



Spark-Ignited Engines

Lean Burn Spark Ignited Natural Gas Technology

Main Benefits:

- **Low emissions of NOx compared to diesel**
  - 50-60% reduction compared to pre 2002 diesels
  - 30% reduction compared to 2002 diesels equipped with EGR
- **Very low emissions of PM compared to diesel**
  - Achieves <0.01 with OC
- **Noise Reduction compared to diesel**
- **More reliable and efficient than traditional stoichiometric engines**

Lean Burn Spark Ignited Natural Gas Technology

Some Drawbacks:

- **Throttled operation and lower compression ratio means efficiency is reduced, particularly at part load**
- **BMEP capability is reduced, leading to traditionally lower torque at low speed**

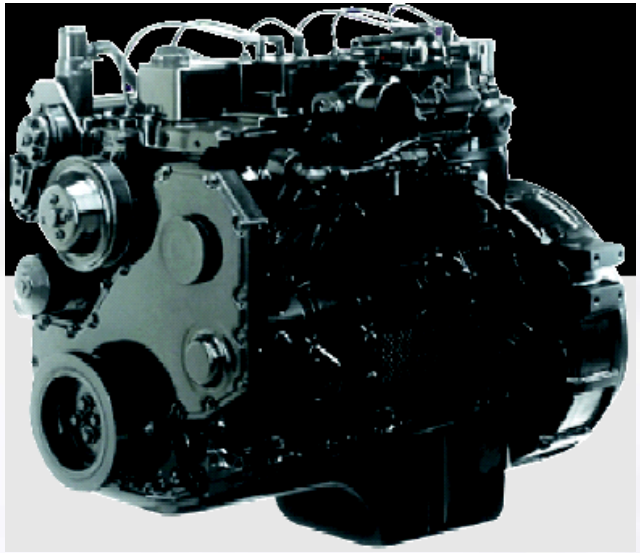
Nevertheless SI lean burn engines are providing:

- **Unmatched emissions reductions compared to diesel**
- **Performance and power needed for mid-range heavy-duty applications (transit buses, delivery vehicles, shuttles, sweepers, refuse haulers, school buses, …)**

Plus Technology - Benefits

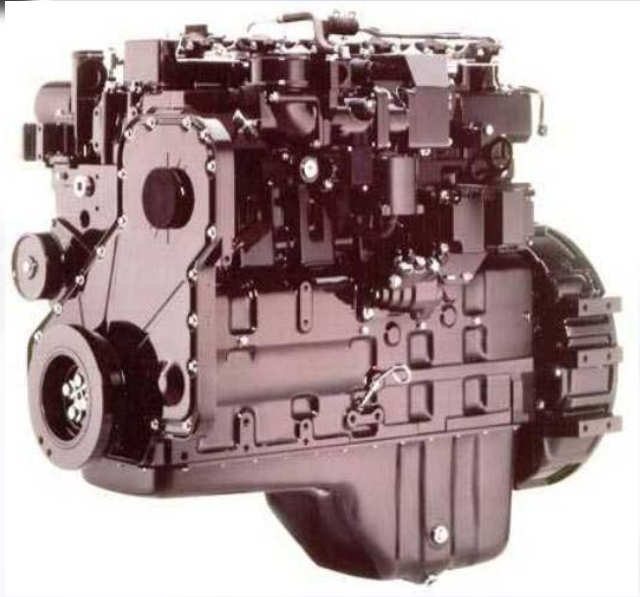
- **State-of-the-art spark ignition/control system**
  - Lean burn, for fuel economy & emissions
  - State-of-the-art electronic engine management with full control of air/fuel handling
  - Increased speed, memory & diagnostic capabilities
  - Electronic throttle (drive-by-wire)
    - Increased diagnostic capabilities
    - Faster response and easier installation for bus/truck manufacturers
    - Woodward governor eliminated
  - Capable of operating on lower quality natural gas
    - CR of 10:1 and knock sensing enables methane number as low as 65
  - Improved reliability and consistency
    - Engine back pressure compensation
    - Fuel supply pressure monitoring
    - Intake manifold temperature monitor and protection
    - Supply voltage monitoring
    - Adaptive learn

B Gas Plus



Model	Horsepower	Peak Torque (ft-lbs)
B5.9-195G+	195 @ 2800	420 @ 1600
B5.9-200G+	200 @ 2800	465 @ 1600
B5.9-230G+	230 @ 2800	500 @ 1600

C Gas Plus



Model	Horsepower	Peak Torque (ft-lbs)
CG-280	280 @ 2400	850 @ 1400
CG-275	275 @ 2400	750 @ 1400
CG-250	250 @ 2400	750 @ 1400
CG-250	250 @ 2400	660 @ 1400

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Emissions Certification

- **C Gas Plus first engine to achieve 2004 EPA levels**
  - ULEV & Optional Low NOx certified with catalyst
  - Euro 3 Q3/02 with Methane Catalyst
- **B Gas plus**
  - ULEV & Optional Low NOx certified with catalyst
  - Euro 3 Q3/02 with Methane Catalyst

Future SI Engines

Our vision is to develop systems that are simpler and cheaper than what is needed on diesels to meet 0.2 g /bhp-hr NOx

Received Funding for 2 SI projects:

- **Application of NOx after-treatment to Lean-Burn SI engines**
  - Currently being tested in laboratory
- **Air-Fuel Ratio Management for reduced NOx emissions**
  - Contract being negotiated

2. High Pressure Direct Injection

"The reliability and performance of diesel with the ***cleanliness*** *and* ***cost-effectiveness*** *of natural gas."*

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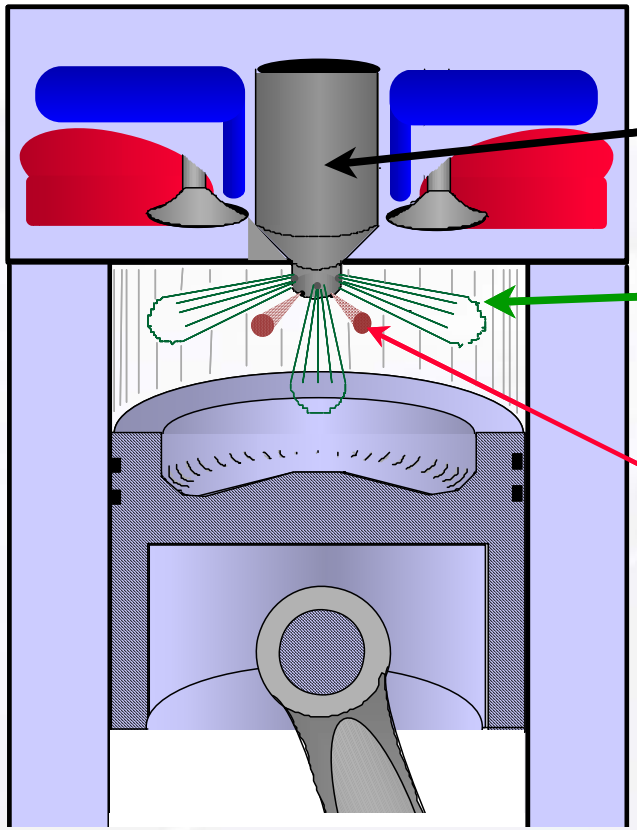
High Pressure Direct Injection Technology



Pilot-Ignited High-Pressure Direct Injection

- **Natural gas injected at high pressure at end of compression stroke**
- **Pilot diesel injected just prior to natural gas to provide ignition**
- **Engine remains the same**
  - **Same high power and torque**
  - **Same high efficiency**
  - **Diesel cycle, not Otto cycle**
    - **not knock limited**
    - **not sensitive to natural gas composition**
- **40% less NOx**
- **60% less PM**
- **20% less CO_2**

than under diesel operation

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HPDI Approach

"Keep the engine, but change the fuel!"

- **No changes to base engine**
  - only replace diesel fuel system
- **Same proven engine components**
  - turbocharging, air handling
  - electronic controls, etc…
- **Provide high power, torque & of the Diesel cycle gas, but with**
  - lower emissions
  - lower fuel prices

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Some Advantages and Disadvantages

Key Advantages of Direct Injection over Homogeneous Charge Approaches:

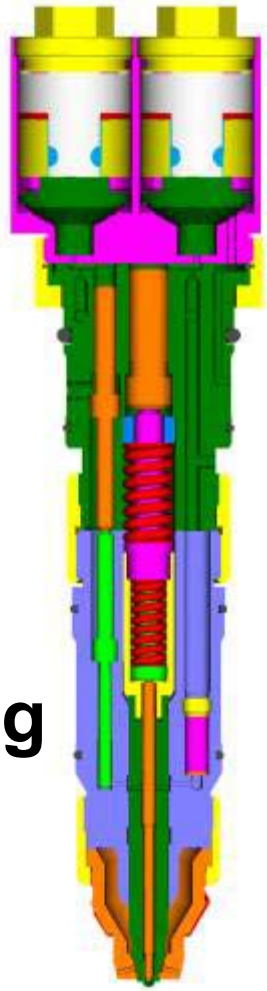
- Not knock limited – 10 to 30% higher torque capability
- Less Sensitive to variations in natural gas composition – no knocking risks
- Performance and emissions much less dependent on precise control of A/F over entire engine load-speed range
- No throttling and compression ratio reduction affecting fuel efficiency (compared to SI)

Some Disadvantages of Direct Injection over Homogeneous Charge Approaches:

- Some unique components must be developed for high-pressure gas handling
- Cannot run on diesel only (compared to Dual-Fuel)

High-pressure gaseous injector with pilot fuel

- Hydraulically actuated, electronically controlled combined injection valve
- Common rail technology
- Unique concentric needles design
- Fits in same way as diesel injector
- Diesel fuel used to provide ignition, actuation, lubrication, cooling, and sealing
- Independent control of pilot and gas injection pressure, timing and metering



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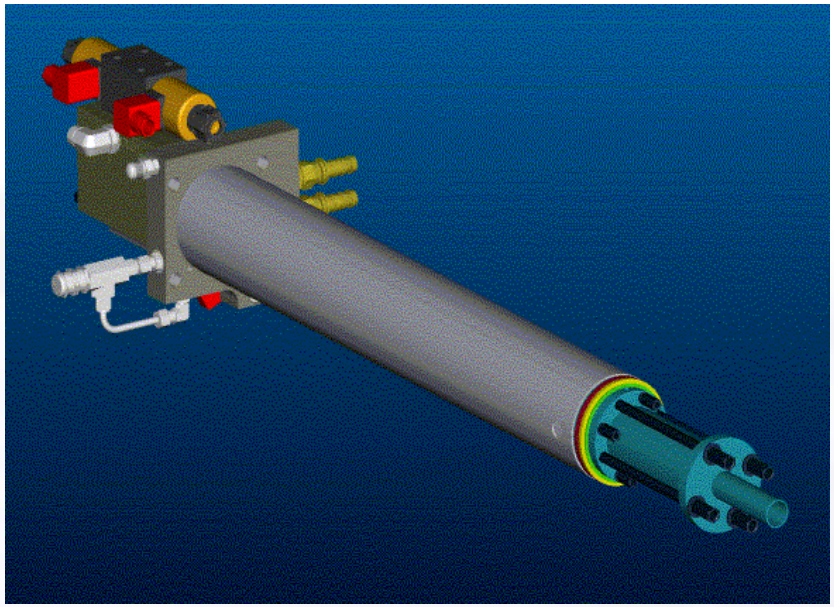
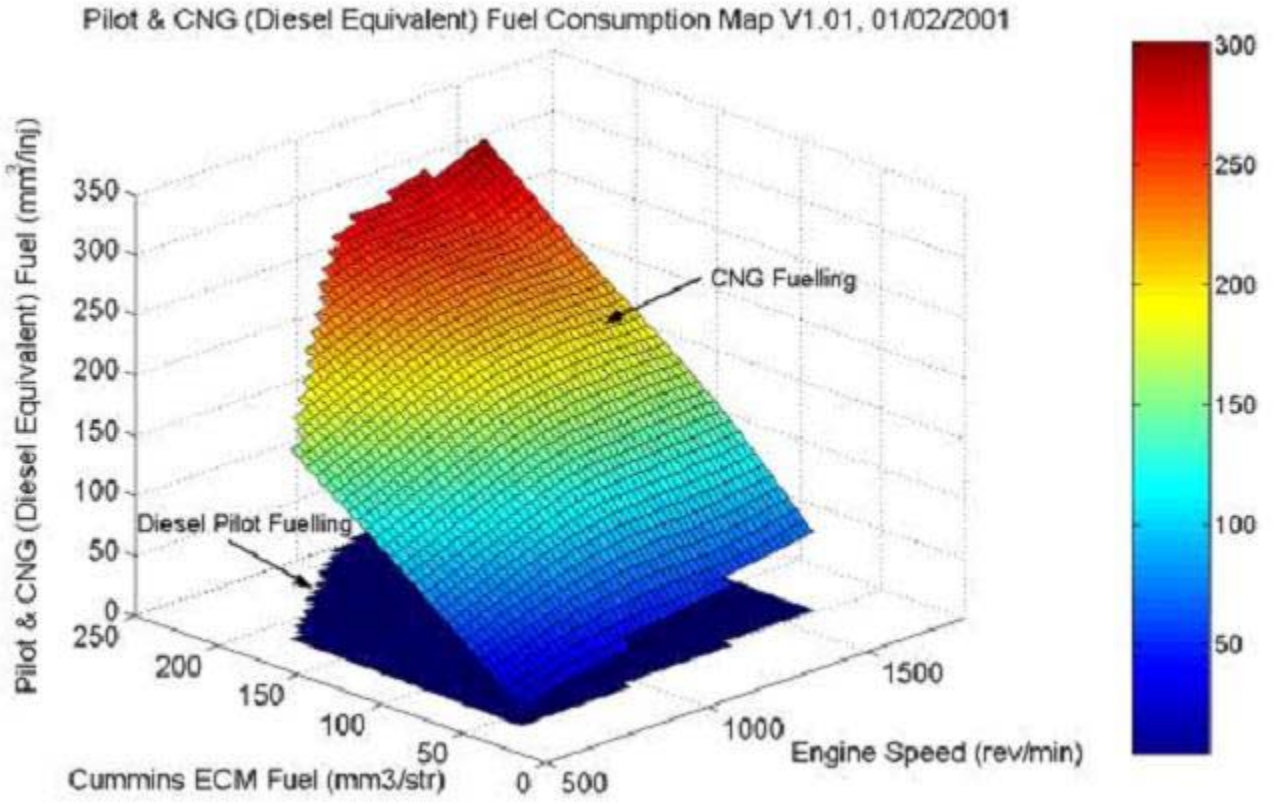
LNG Pump



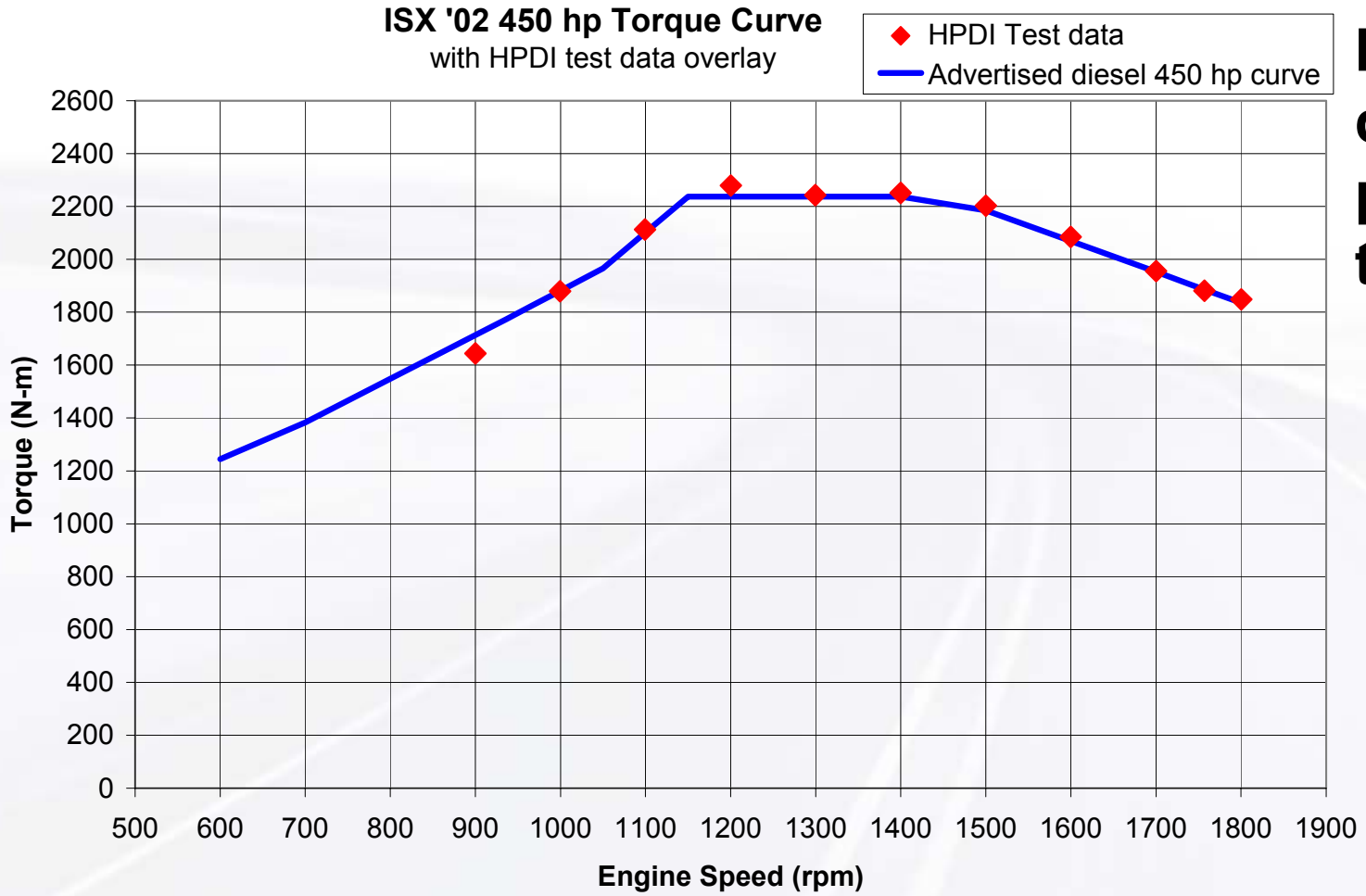
- **Hydraulically Driven Cryogenic Pump**
  - **Simple, standard industry hydraulic cylinder parts**
  - **Cryogenic seals evolved over 5 years of high pressure pump development**
- **Single-stage, slow reciprocating design**
  - **provides for long seal life due to slow speeds and LNG super-cooling**
- **Power requirement to pump LNG to 200 bar is less than power requirement to bring diesel to 1500 bar.**
- **Evaluating pump integrated into tank**
  - No pump cool down time
  - Integrated Vaporizer
  - Integrated plumbing

Gas and Pilot Diesel Flows

- Only enough diesel fuel to initiate ignition
- 2% at full load
- 5-6% pilot on typical cycle
- No idling or running solely on diesel fuel

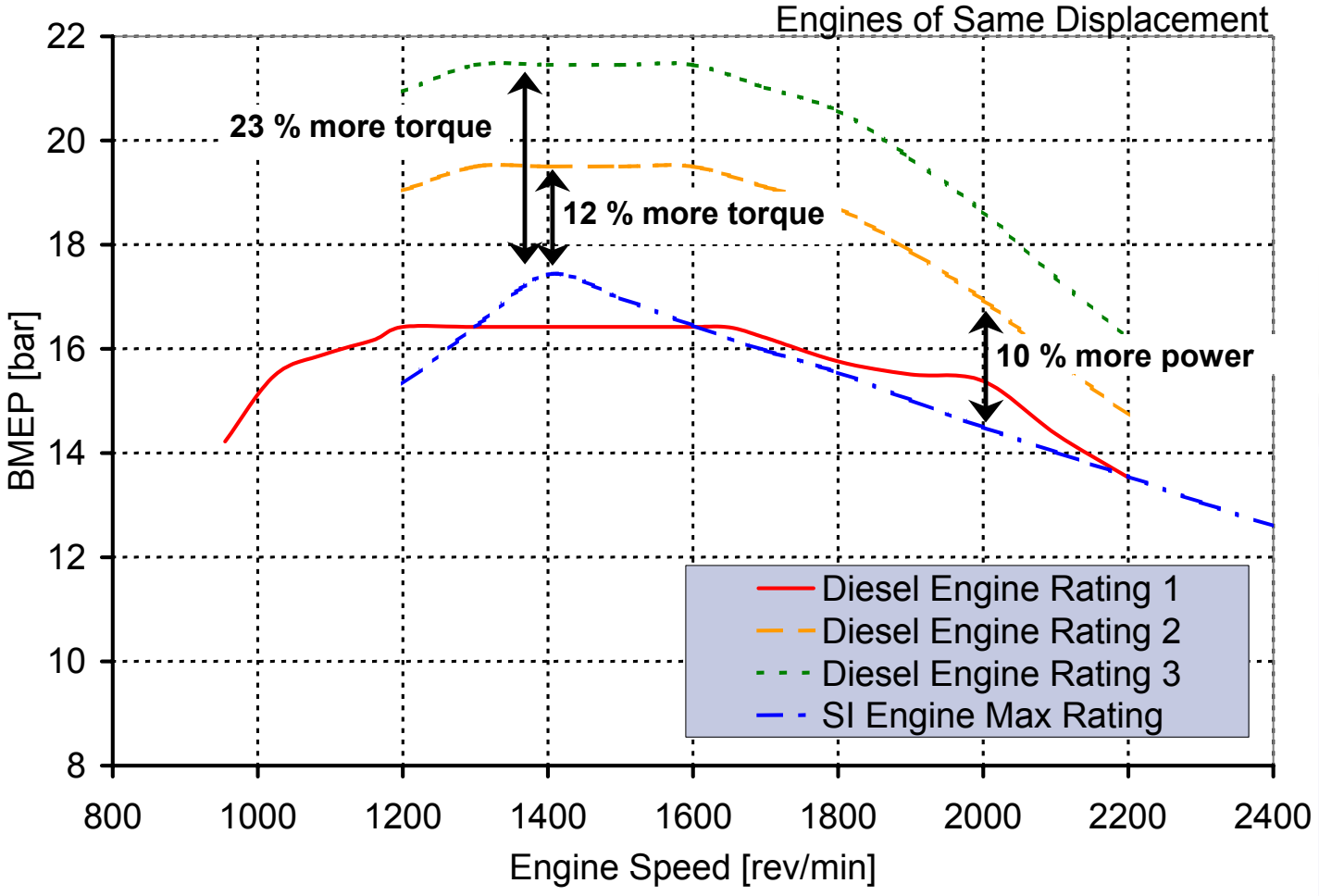


Performance (HPDI vs Diesel)



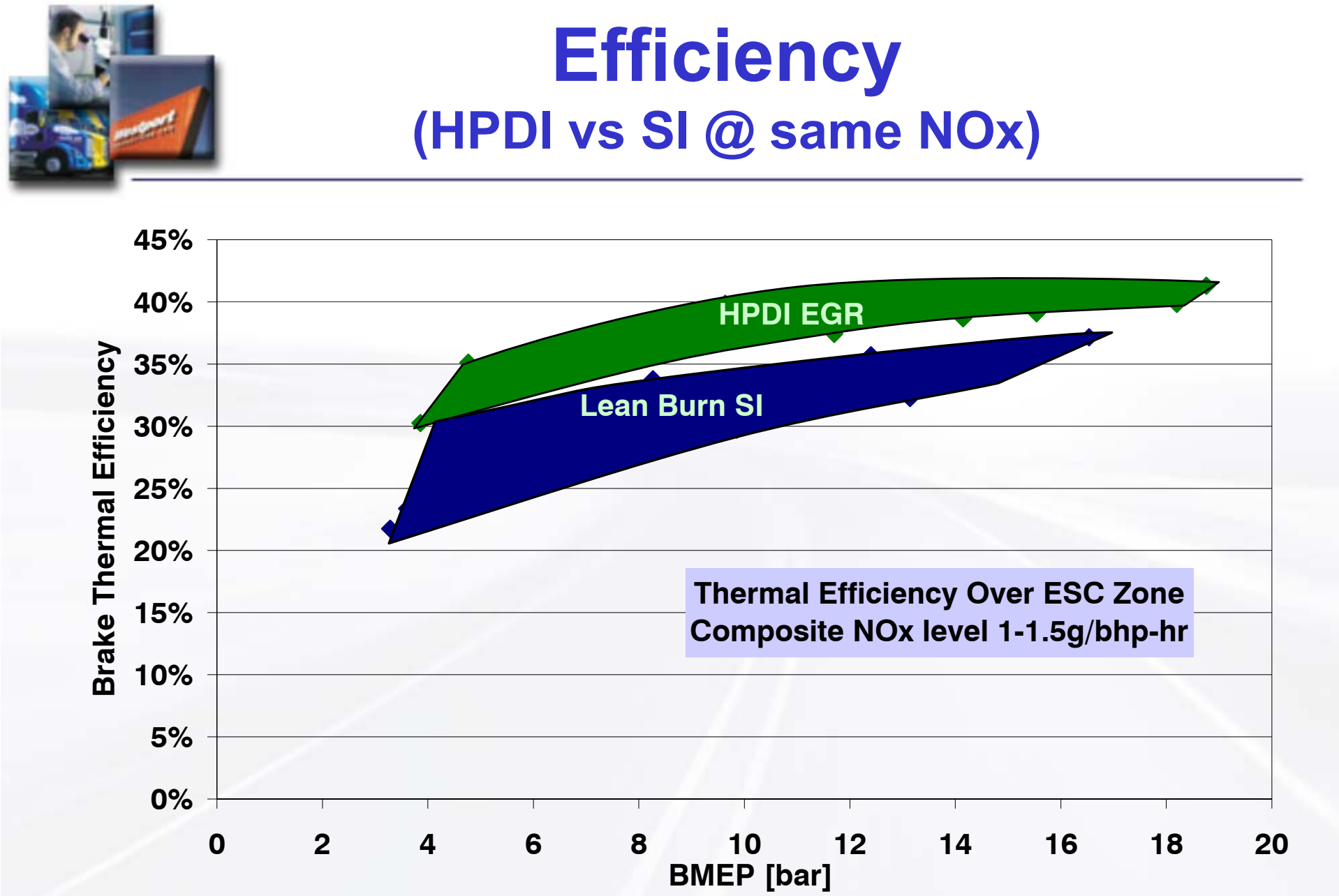
Match base diesel power and torque

Performance (DI vs SI)



Diesel engines can be rated higher than SI for heavy duty applications

Efficiency
(HPDI vs SI @ same NOx)



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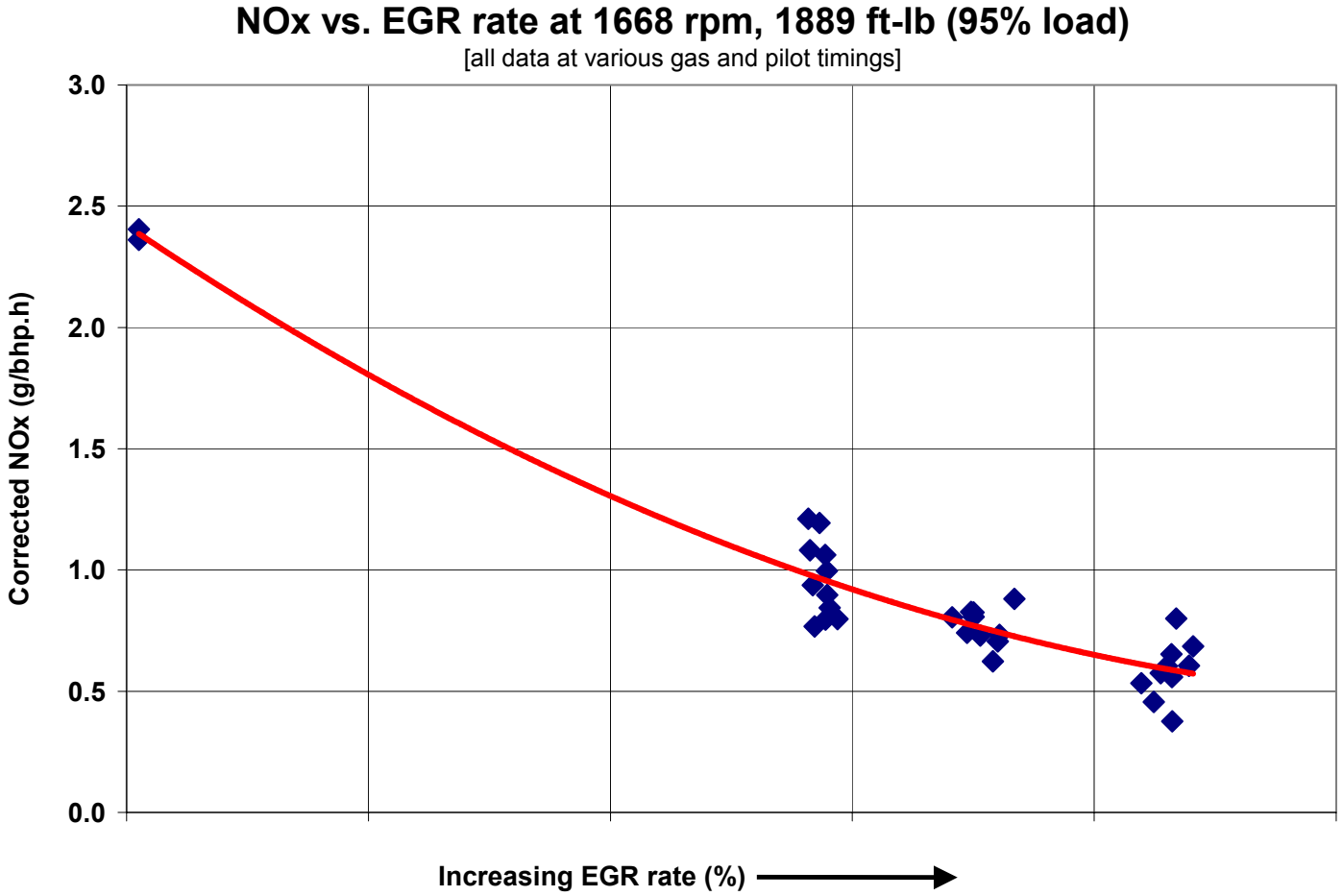
Emissions – ISX EGR engine



- NOx is typically reduced 40% over diesel
- EGR effective to reduce NOx from HPDI

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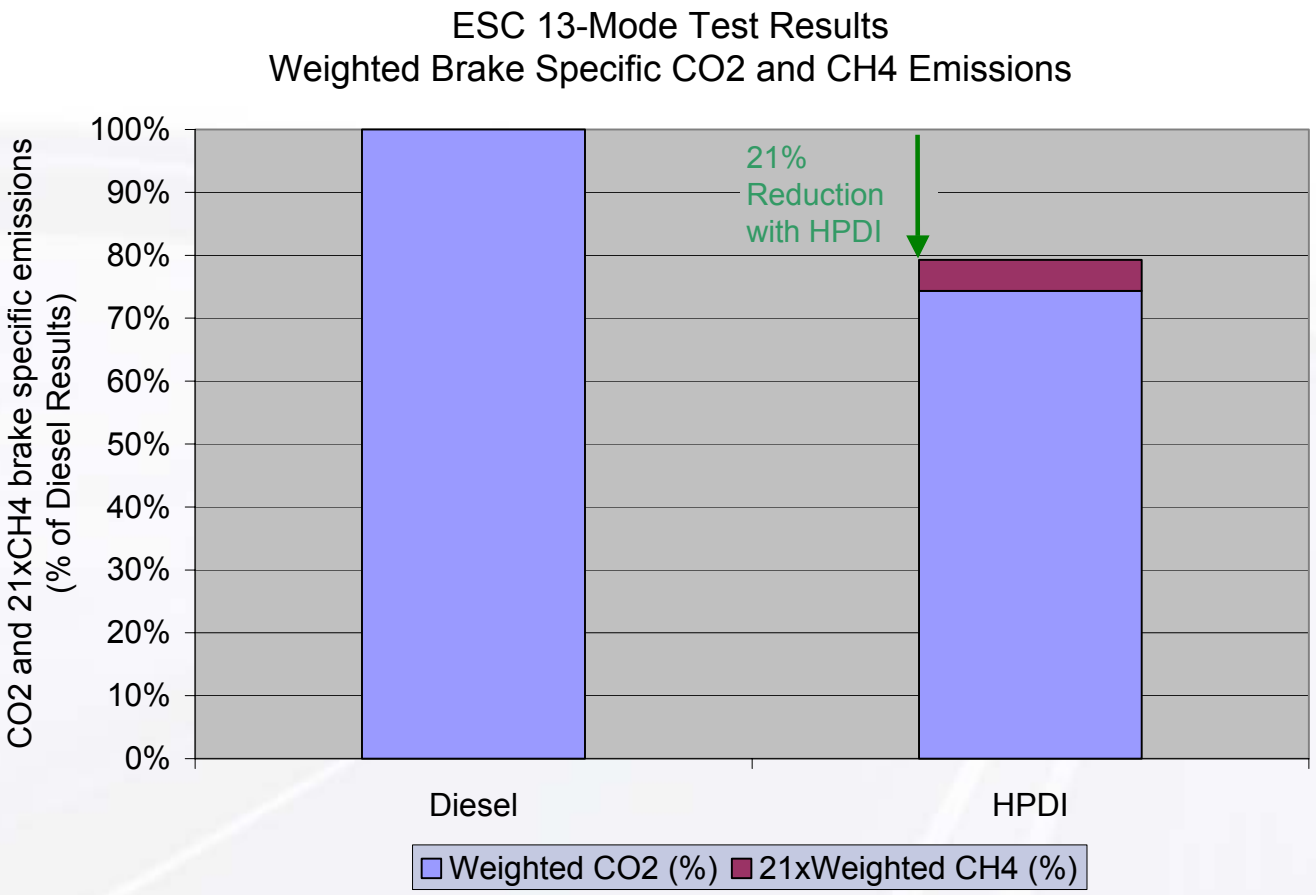
Emissions – ISX EGR engine



- **HPDI with pilot has low engine out methane emissions ~ typically 1 g/bhp-hr**
- **Cycle GHG emissions are approximately 20% lower than diesel**

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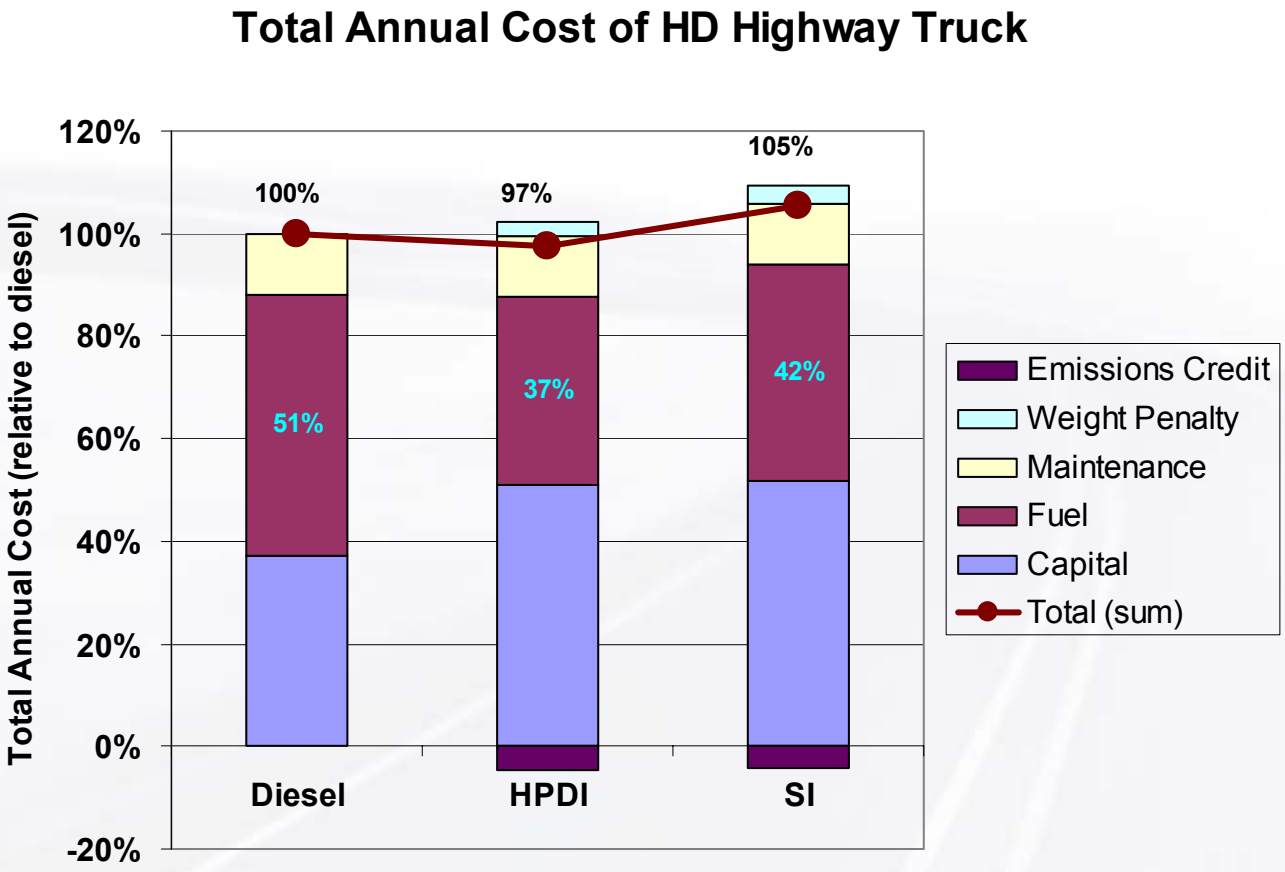
Emissions – ISX EGR engine

- HPDI not as good as SI for PM
- Typically, PM are 60% lower than for diesel
- Last certification data were 0.03 g/bhp-hr
- Unclear today whether oxidation catalyst or diesel particulate filter is best long term solution to bring PM < 0.01 g/bhp-hr.

Owning and operating costs



Scenario

- Heavy Duty Class 8 truck
- Premium consistent with industry trends
- HPDI at 40% lower NOx compared to 2002 certified diesel engine
- 100,000 miles a year
- 5.5 mpg (for diesel)
- 7 year life
- NOx emissions credit of $6000/tonnes
- CO2 emissions credit of $10/tonnes
- No credit for reduced oil imports or PM reduction
- Diesel at $1.25/gallon
- LNG 30% cheaper

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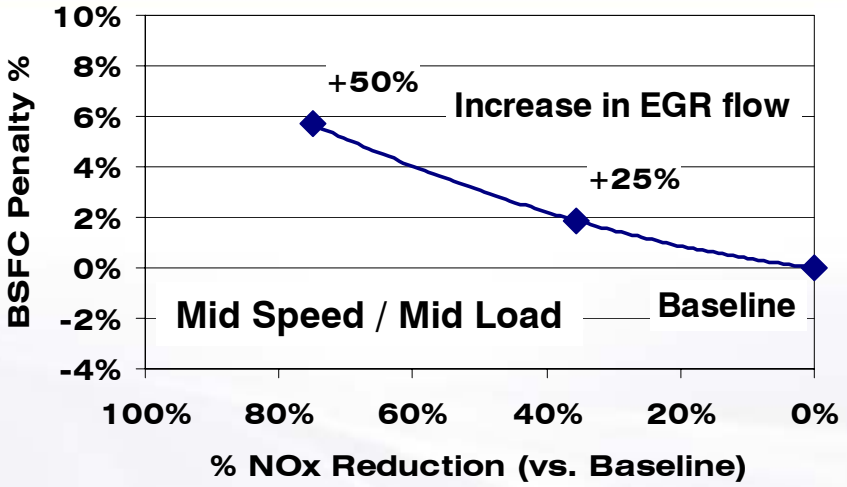
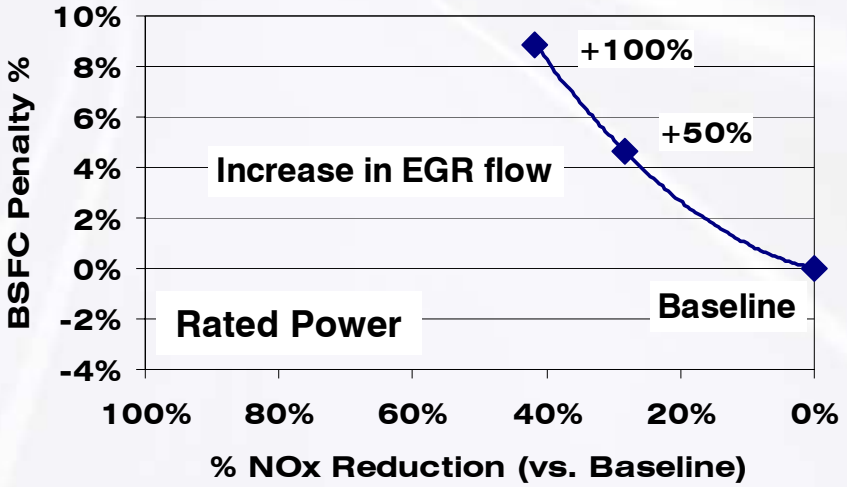
Paths to Further Emissions Reductions

- **Opportunities for further in-cylinder NOx reduction (EGR)**
- **NOx aftertreatment is required to meet 0.2g/bhp-hr target**
  - Engine vs aftertreatment balance must be evaluated
- **HPDI Compatible with particulate filters**
  - CNG and LNG already low sulfur
  - Could provide ultra-low PM and very low number of ultrafine
- **We have been active in concept-level research activities over past year**

Impact of Additional EGR on NOx

- Increasing EGR over "standard EGR rates" results in significant NOx reductions
- Responses vary at different speeds / loads
- Project funded by NREL / SCAQMD, target 0.5 g/bhp-hr NOx





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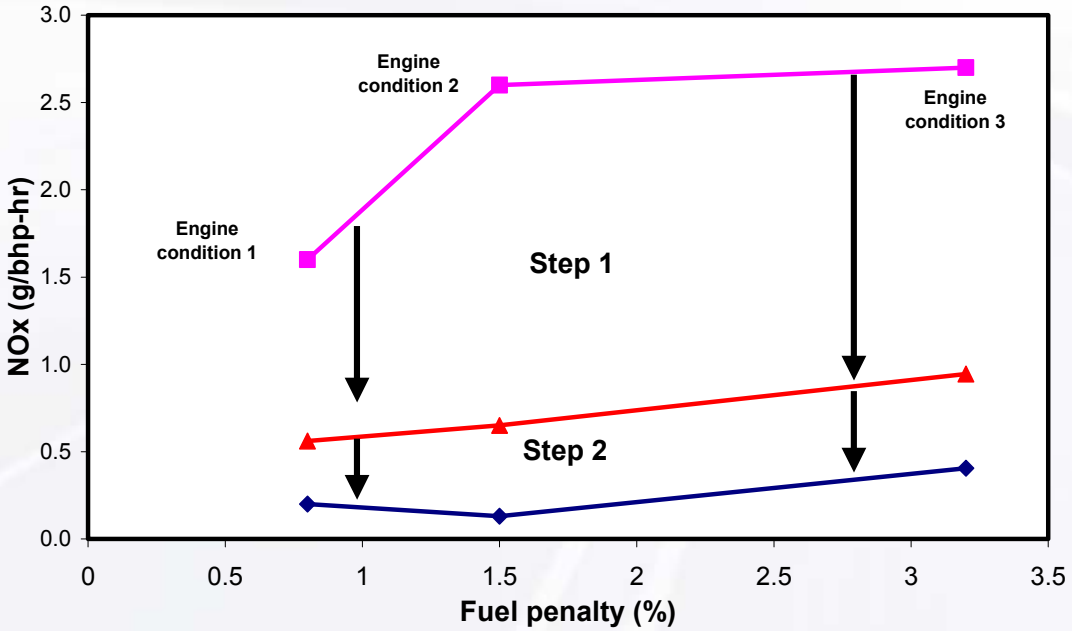
NOx Emissions Control System

NOx after-treatment systems being developed for diesels are compatible with HPDI – Simpler and less penalizing systems needed.



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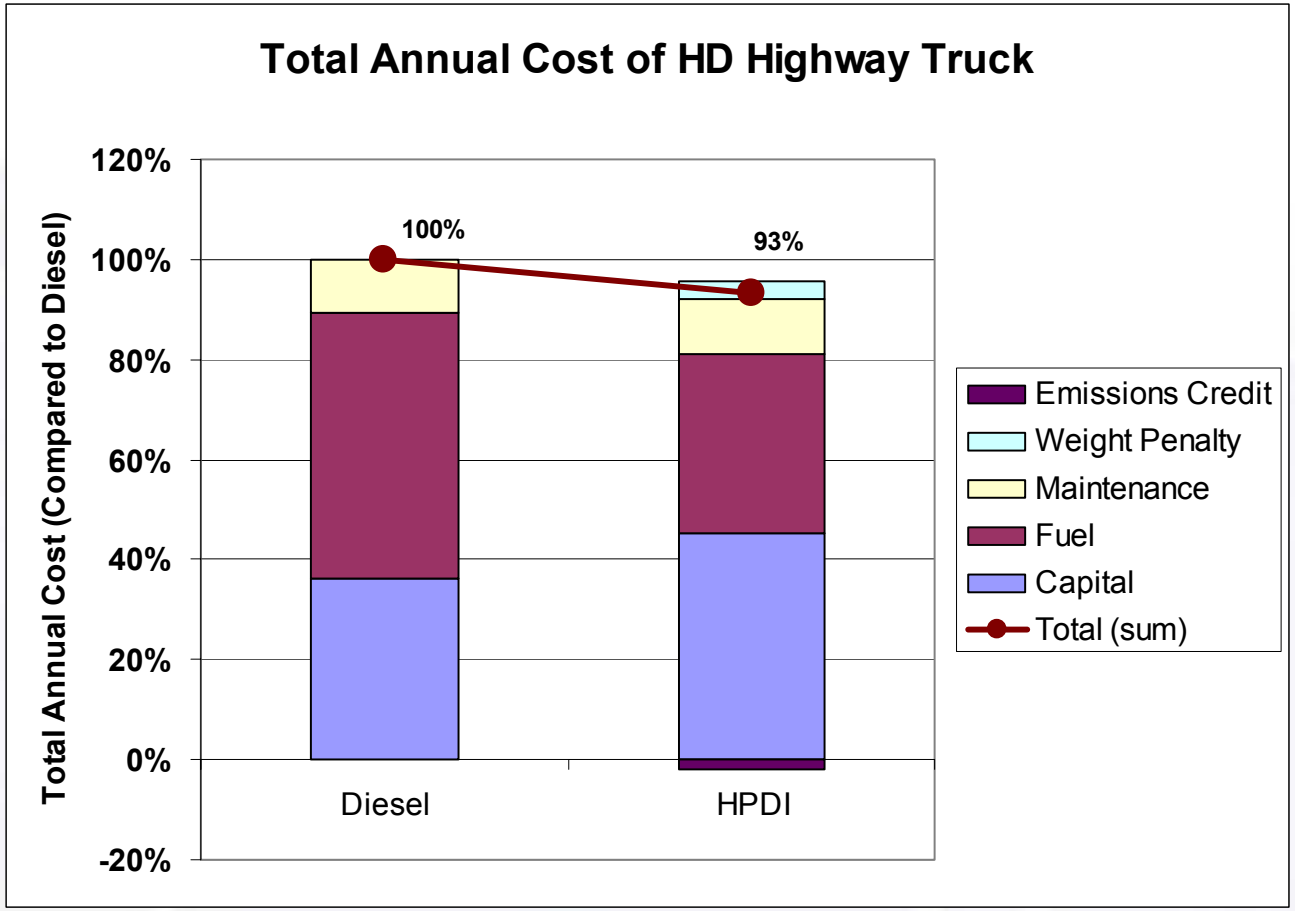
Improving Owning and operating costs at 2010



Scenario

- Heavy Duty Class 8 truck
- HPDI at same NOx compared to 2010 certified diesel engine
- 100,000 miles a year
- 5.5 mpg (base diesel)
- 7 year life
- CO2 emissions credit of $50/tonnes
- ULSD at $1.35/gallon
- LNG 30% cheaper
- No offset for reduced oil imports
- Premium reduced compare to 2002 due to greater volume, and adjusted for different emissions control systems

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Summary

CWI Natural Gas Engines

- **SI Engines have demonstrated Capabilities and Environmental Benefits in Mid-Range vehicles**
- **DI Engines provide benefits in higher fuel usage Heavy-Duty applications by maintaining cycle efficiency, allowing for reduced fuel costs, as well as:**
  - Maintaining diesel torque, power, transient response (driveability)
  - Providing GHG reduction
  - Maintaining the characteristics that make diesels so reliable:
    - Low exhaust temperature
    - Pilot ignition

Target for the future

- **There will always be a technology cost premium for low-emission or alternative fuel solutions until volumes are equal**
- **But Clean Diesels will also cost more – gap is narrowing**
- **Natural gas has two unique value propositions to make it economically attractive**
  - Lower emissions or energy security issues attracts credits and offsets in some jurisdictions
  - Natural gas will likely remain cheaper than diesel

Target for the future

These value propositions provide an opportunity for natural gas engines to operate at lower life cycle cost compared to "clean diesels"

We need as an industry to:

- **Find ways to reduce costs of natural gas engines and refuelling facilities despite lower volumes**
- **Find ways to make our products more reliable**
- **Creatively use the lower inherent emissions of natural gas to develop combustion systems that are less costly, more reliable and less penalizing than those needed for diesels**

Thank you!

Questions?